Impact of the higher mean climate sensitivity in CMIP6 models on the Southern Annular Mode

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Timescales of SAM response to abrupt-4xCO_2

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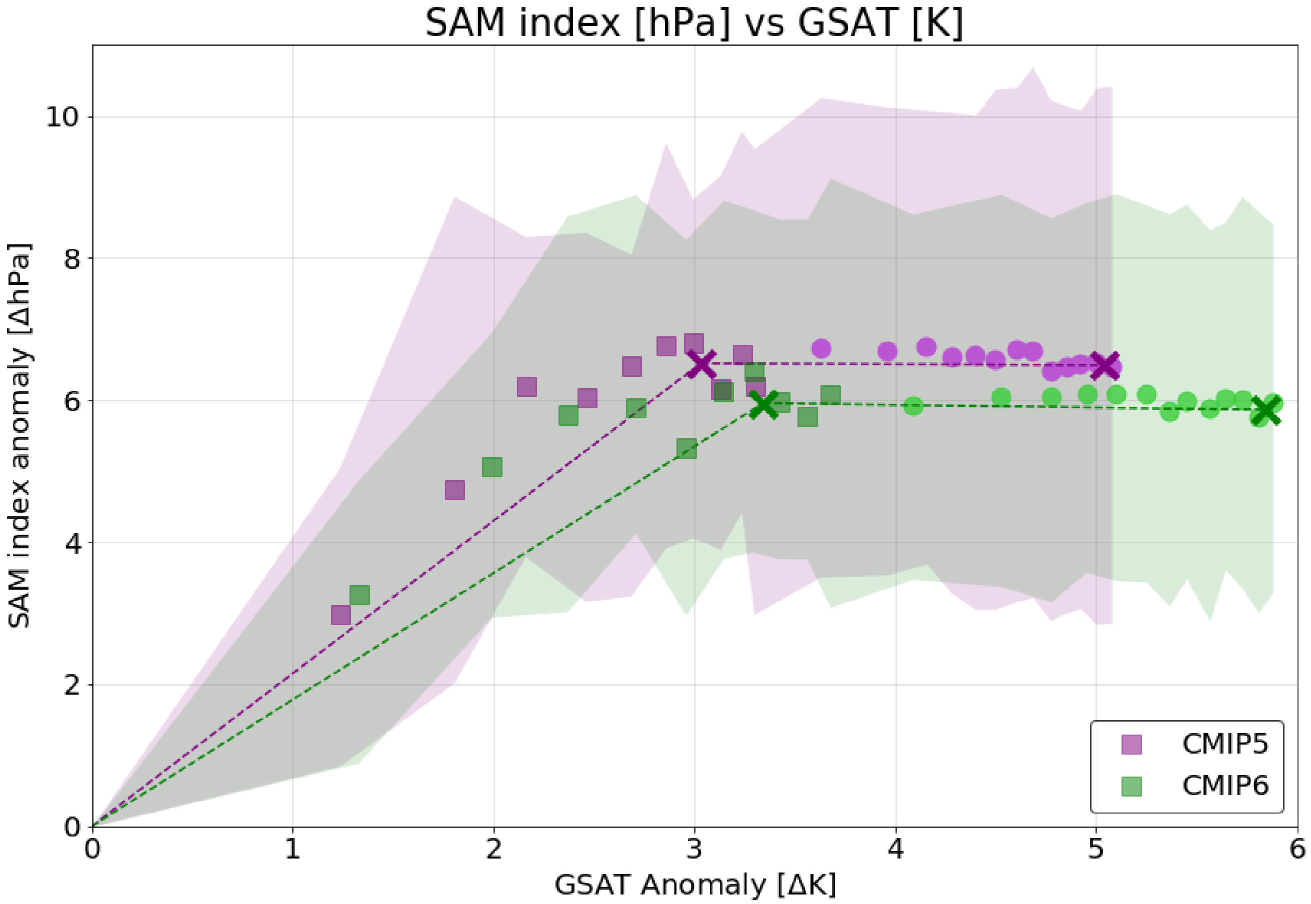

Figure 1: Multi-model mean SAM index [hPa] vs. GSAT [K] anomalies in abrupt-4xCO2 experiment compared to pre-industrial control. Squares show annual means for years 1-10 and dots show decadal means for years 20-140. Crosses denote the averages of years 5-10 and years 121-140 with dashed connecting lines. Shading denotes the 75% model range of SAM index. Purple shows CMIP5 and green shows CMIP6.

Key points:

- Most of the long-term increase in the SAM index occurs in the first decade following an abrupt-4xCO2 forcing.
- Only around half of the long-term increase in global mean surface temperature (GSAT) occurs during this period.
- The multi-model mean increase in the SAM index is **smaller** in CMIP6 than in CMIP5 despite the GSAT change being **larger** in CMIP6 than in CMIP5.

SAM = P*(40°S) – P*(65°S)

Where: P* = zonal mean sea level pressure at defined latitude band

References:

[1] Ceppi, P. et al (2018) https://doi.org/10.1175/JCLI-D-17-0323.1

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GSAT normalised SAM index changes

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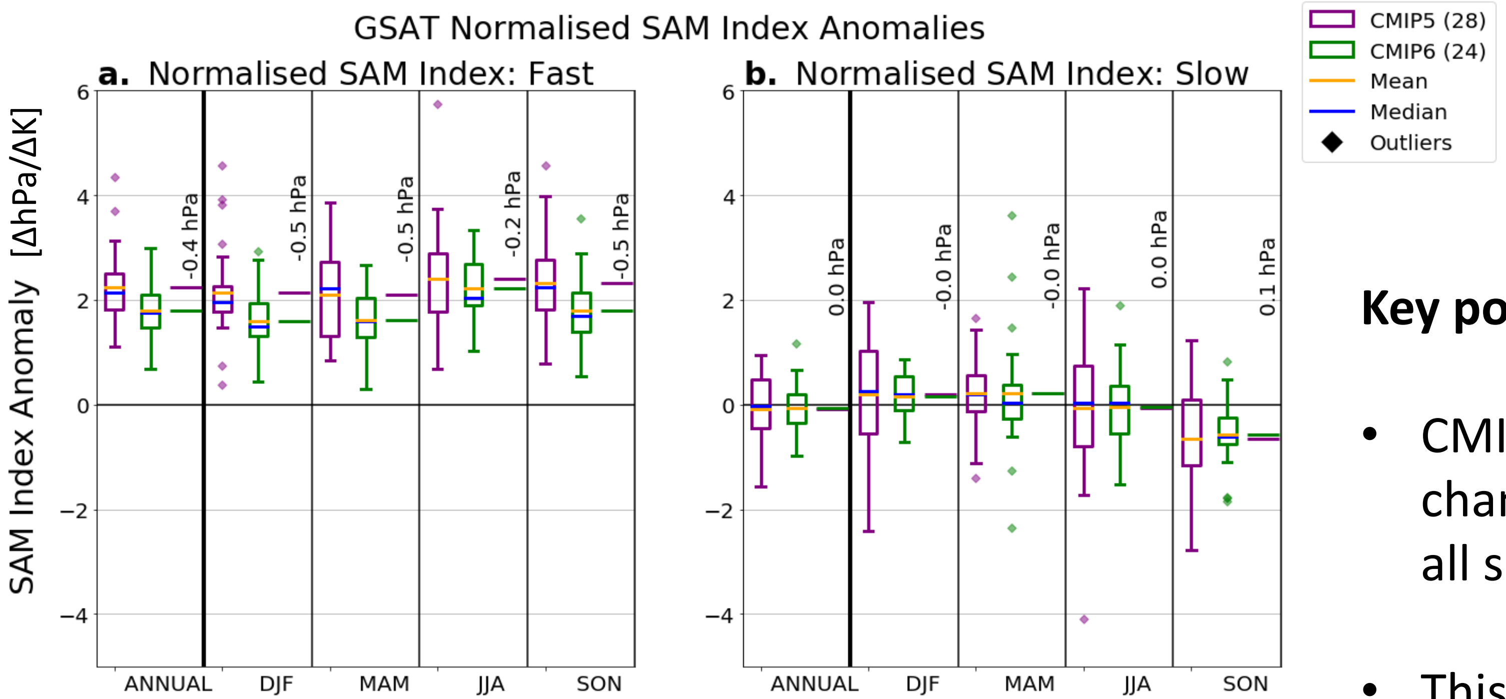

	Ann	DJF	MAM	JJA	SON
P value	**0.014**	**0.014**	**0.019**	0.431	**0.022**

Ann	DJF	MAM	JJA	SON
0.943	0.891	0.987	0.972	0.689

Figure 2: Boxplots of the fast (years 5-10) and slow (years 121-140 minus Fast response) annual and seasonal mean SAM index anomalies in the 4xCO2 experiment. Values are normalised by the respective GSAT change in each period [ΔhPa/ΔK]. Data are for CMIP5 (purple) and CMIP6 (green). Orange and blue horizontal lines denote the mean and median, respectively. Box and whiskers denote the interquartile and 95th percentile ranges, respectively. The difference between the CMIP5 and CMIP6 multi-model means (MMM) is shown to the right of the boxes. P-values for the differences between CMIP5 and CMIP6 models are shown in the tables.

Key points:

- CMIP6 models show significantly smaller SAM changes per degree of warming than in CMIP5 in all seasons, except in austral winter (JJA)
- This difference is entirely manifested in the first decade when most of the SAM increase is seen. There are no differences in the multi-decadal response.

Surface temperature responses per degree global warming

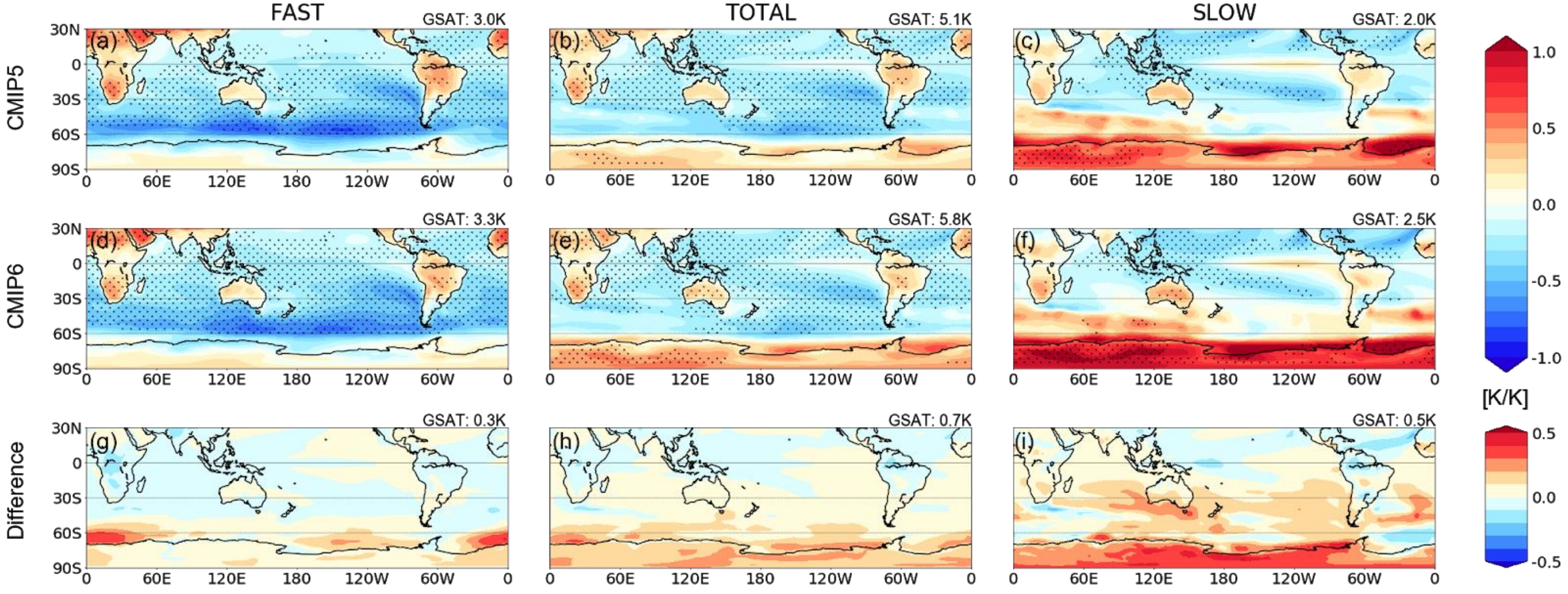

Figure 3 – (left) Fast (years 5-10), **(centre)** total (years 121-140) and **(right)** Slow (Total minus Fast) annual mean surface temperature anomalies normalised by GSAT change [$\Delta K/\Delta K_{GSAT}$]. Data show **(top)** CMIP5, **(middle)** CMIP6 and **(lower)** CMIP6 – CMIP5. Anomalies have been subtracted by 1 so that negative values show changes less than the global mean and vice versa. The GSAT change in each period is shown in above the header. Stippling indicates where >90% of models agree on sign of change.

<u>Key points</u>:

FAST period:

- Warmer Southern Ocean in CMIP6 vs. CMIP5 (e.g. Weddell Sea region)
- Cooler midlatitudes and tropics in CMIP6 vs. CMIP5

SLOW period:

- Warmer northern midlatitudes in CMIP6 vs. CMIP5.
- Cooler Weddell Sea region in CMIP6 vs. CMIP5
- Warmer Antarctic surface in CMIP6 vs. CMIP5

Temperature gradient changes

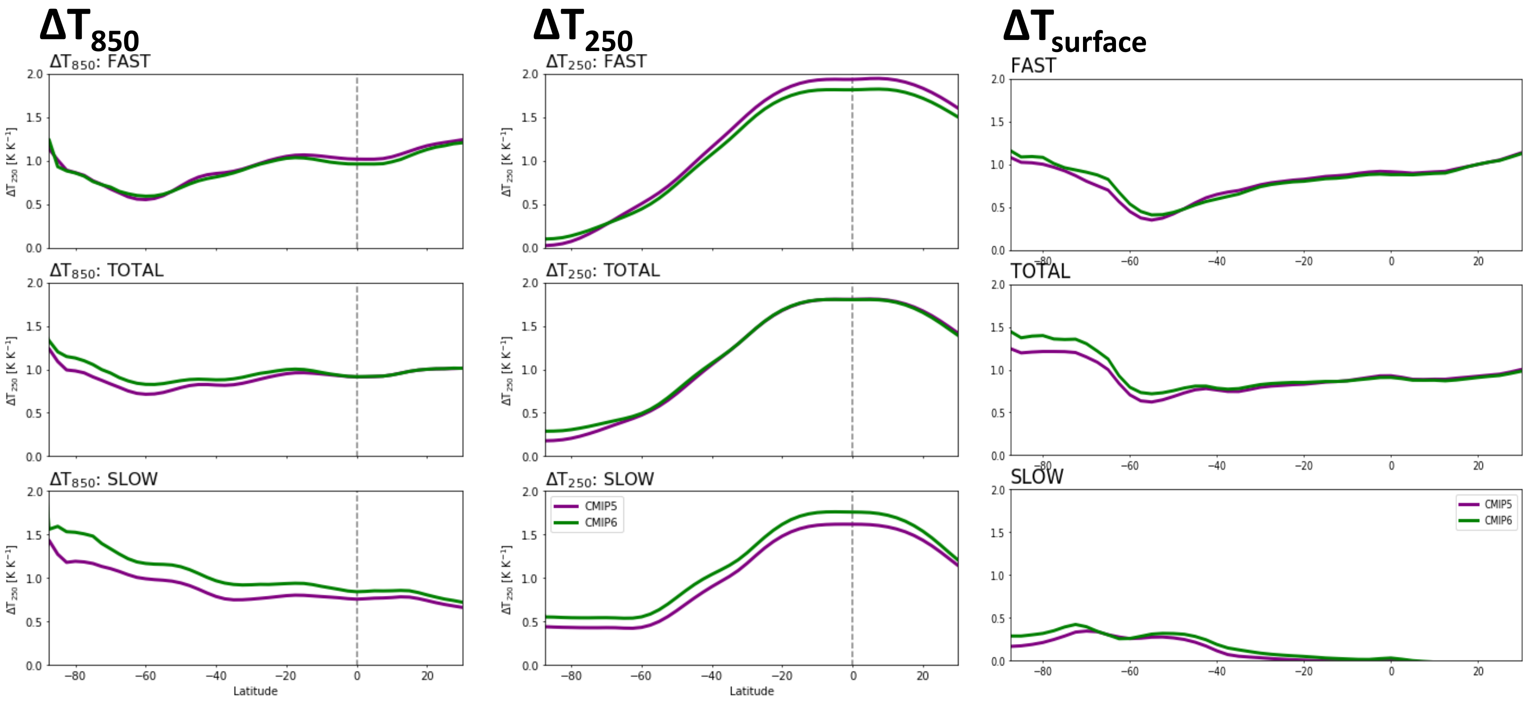

Figure 4: (top) Fast (years 5-10), **(middle)** Total (years 121-140) and **(bottom)** Slow (Total – Fast) annual mean abrupt-4xCO2 temperature anomalies normalised by GSAT change [$\Delta K/\Delta K_{GSAT}$]. Data are shown at **(left)** 850hPa, **(middle)** 250hPa and **(right)** the surface. CMIP5 (purple) and CMIP6 (green).

Key Points:

FAST:

- Tropics-to-pole temperature gradient **increases** at all levels in CMIP5 and CMIP6
- **Smaller** temperature gradient change per degree of warming at all levels in CMIP6 vs. CMIP5

SLOW:

- Temperature gradient change per degree warming has opposite sign to the fast period at lower levels (i.e. gradient **decreases** per unit GSAT change) – Antarctica and Southern Ocean begin to warm up on longer timescales.
- **Larger** lower level temperature change per unit GSAT change in CMIP6 vs. CMIP5
- “Tug of war” between lower and upper level temperature gradient changes – small net effect.

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IGCM4 model sensitivity runs

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To test the effect of the different CMIP5 and CMIP6 4xCO2 sea surface temperature (SST) anomaly patterns on the SAM index we ran the Reading Intermediate General Circulation Model 4 (IGCM4):

Experiments 1/2

- Control (CMIP5 or CMIP6 piControl SSTs)
  - pre-industrial CO_2 concentrations
  - two piControl runs with muliti-model mean SSTs of CMIP5 or CMIP6 pre-industrial control runs imposed
- 4xCO2 with respective CMIP5/6 4xCO2 **'Total'** SSTs
  - Abrupt 4xCO_2 concentrations
  - MMM SSTs from 'Total' period (years 121-140) from respective CMIP5/6 abrupt4xCO2 run imposed
  - Two versions where sea ice regions are either masked (i.e. sea ice is kept fixed) or unmasked (i.e. sea ice can evolve)

Experiment 3

- Control (CMIP5 piControl SSTs)
  - pre-industrial CO_2 concentrations
- 4xCO2 **FAST** (CMIP5 or CMIP6 4xCO2 'Fast' SSTs – Fixed sea ice)
  - Abruptly quadrupled CO_2 concentrations (4xCO2)
  - MMM SST from the CMIP5/6 abrupt4xCO2 'Fast' period divided by respective 'fast' GSAT change then scaled by average GSAT change of CMIP5 + CMIP6.
    - Removes influence of different GSAT responses
    - Fast SST pattern that produces largest SAM index change is imposed
  - Regions covered in sea ice in piControl runs are masked (sea ice fixed)
    - Keeps the experiment simple but excludes some differences in surface temperature anomalies around Antarctica

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IGCM4 response to Total SSTs: SAM Index

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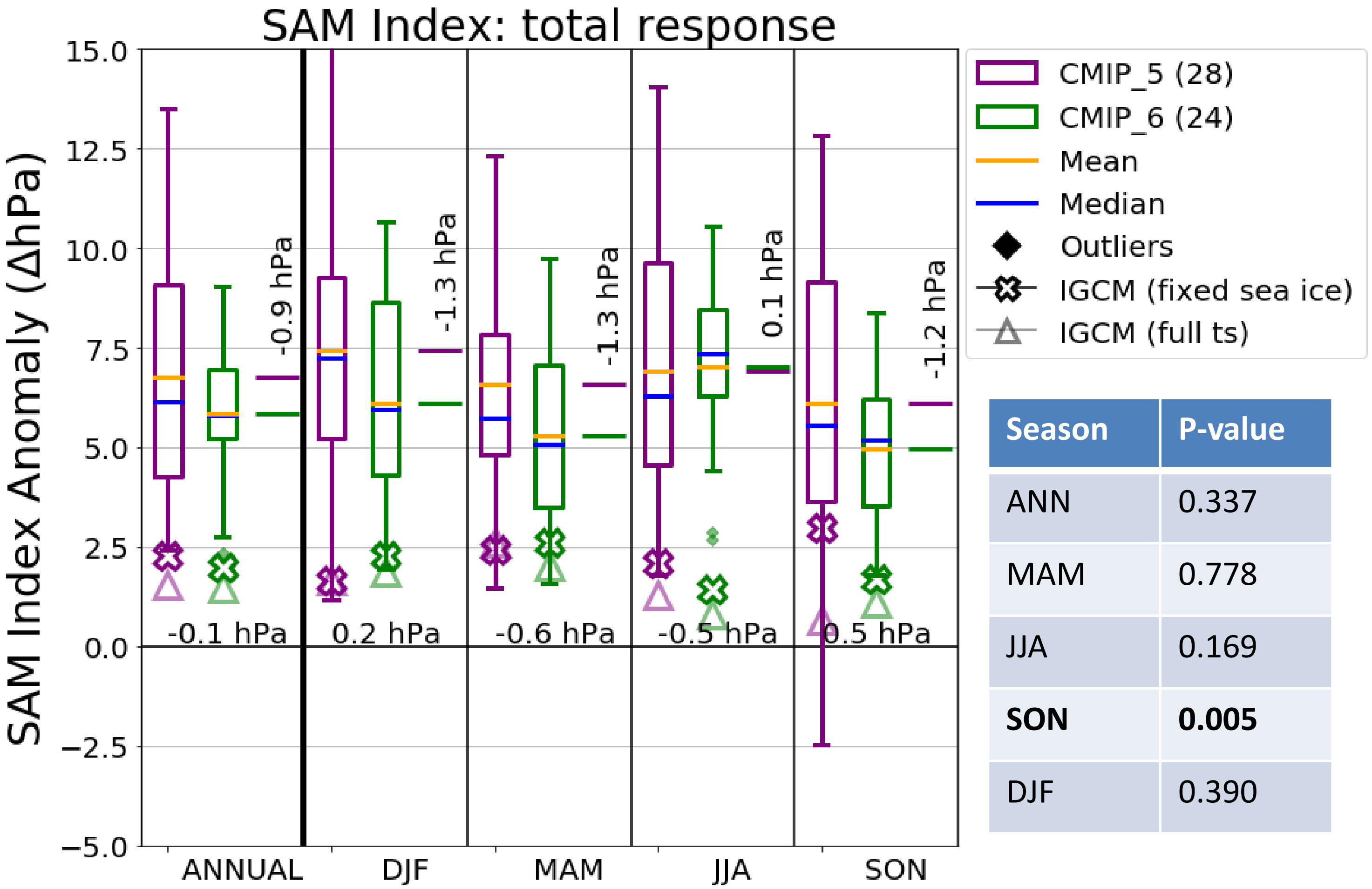


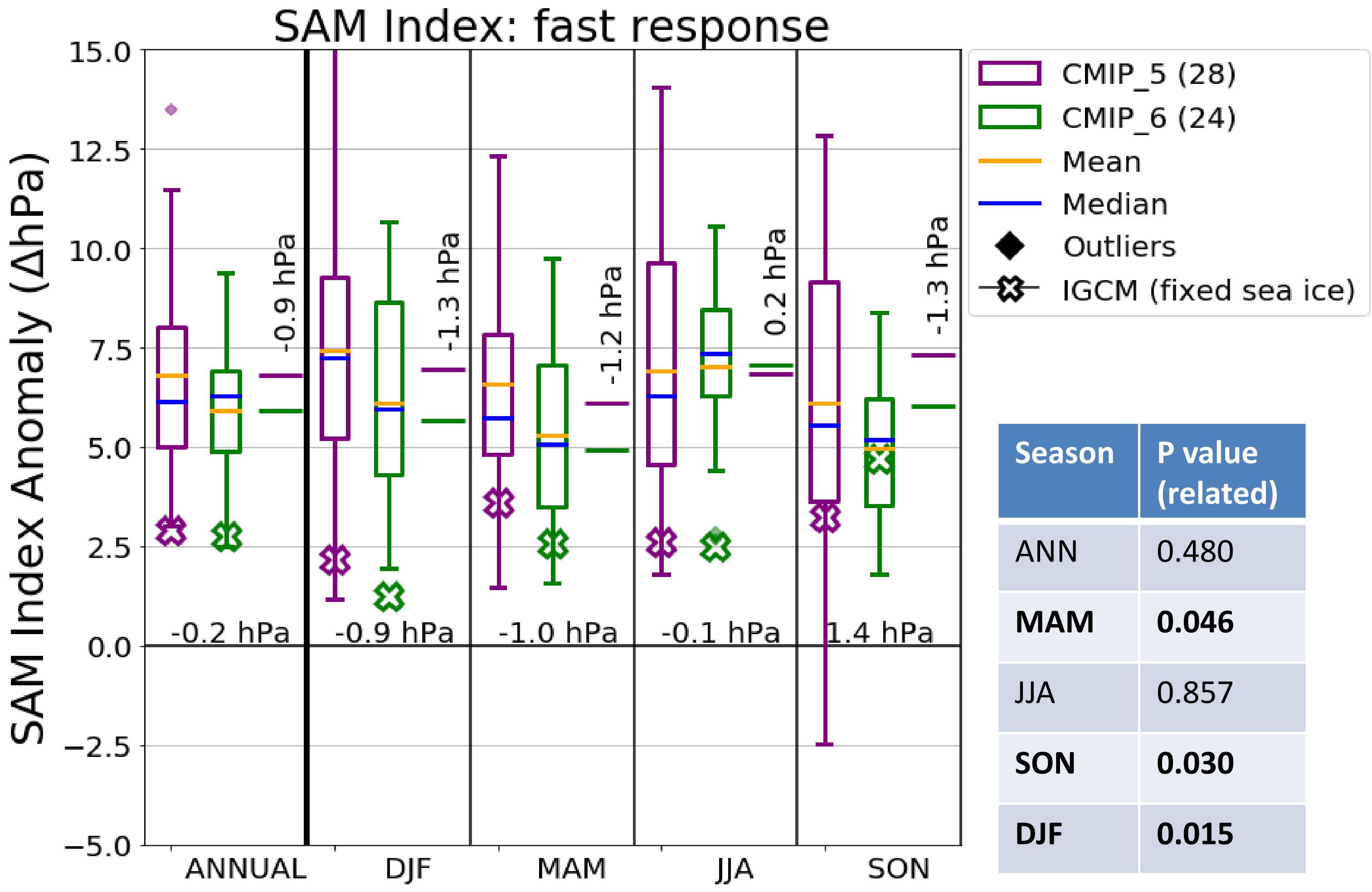
Season	P-value
ANN	0.337
MAM	0.778
JJA	0.169
SON	**0.005**
DJF	0.390

Figure 5: Total SAM index anomalies [hPa] in CMIP5 and CMIP6 models along with IGCM4 experiments. Unfilled crosses show the IGCM runs without sea ice changes; unfilled triangles show runs with sea ice evolving.

Key Points

- IGCM captures sign of difference in SAM index responses between CMIP5 and CMIP6 in the annual mean, winter (JJA) and spring (SON), but not in summer (DJF) and autumn (MAM)
- Only spring shows a statistically significant difference between IGCM responses
- SAM shift is smaller when sea ice is allowed to evolve in IGCM (triangles) compared to when sea ice is fixed (crosses)
- All IGCM responses are on the lower end of the CMIP model spread.

IGCM4 response to Fast SSTs: SAM Index



Season	P value (related)
ANN	0.480
MAM	**0.046**
JJA	0.857
SON	**0.030**
DJF	**0.015**

Figure 6: As in figure 5, but for SAM index anomalies in IGCM4 with 'fast' 4xCO2 SST anomalies imposed. Skin temperature ('ts') fixed in sea ice region.

Key Points:

- Annual mean shows small, statistically insignificant (p=0.7) difference in SAM index response to CMIP MMMs
- However, difference in response is significant in all seasons except JJA (winter) ($p<0.05$)
- The sign of the difference between responses is the same as the difference between CMIP5 and CMIP6 MMMs in the annual mean and all seasons except for SON.

Conclusions and Ongoing Work

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- Most of the increase in SAM index following abrupt-4xCO_2 occurs in the first decade.
- Despite showing higher mean warming, the CMIP6 models produce a weaker increase in SAM on average (i.e., the difference is not congruent with GSAT).
- Differences in meridional temperature gradients in CMIP5/6 may be a factor in explaining the difference between SAM index responses.
  - Ongoing work to investigate this.
- IGCM4 experiments forced with CMIP5 and CMIP6 SST patterns shows this alone cannot explain the different annual mean SAM responses, but there appears to be an effect in some seasons.
  - Note the imposed patterns do not capture SST differences close to Antarctica, where sea-ice changes play a key role for surface temperature trends.
  - Further consideration is that IGCM4 may not represent a mean CMIP model, e.g. its SAM response is at the lower end of the CMIP model spread.
- Modelled jet biases may also play a role in some seasons (see e.g., Simpson and Polvani, 2016; Curtis et al., 2020).

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